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Theoretical and Experimental Studies of
Radiation-Induced Damage to Semiconductor
Surfaces and the Effects of this Damage on
Semiconductor Device Performance

1 March through 31 August 1965

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- FORWARD -

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research activities of the North Carolina State University's

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PUBLICATIONS AND REPORTS
(1 March through 31 August 1965)

R. J. Mattauch, R. W. Lade and G. B. Hoadley, "Tables of Functions for Semiconductor Surface Calculations", Proc. IEEE, 53, p. 743; July, 1965.

R. J. Mattauch, R. W. Lade and G. B. Hoadley, "Tables of $F(U_s, U_b)$ and $G(U_s, U_b)$ Functions for Semiconductor Surface Calculations", Engineering School Bulletin No. 80, N. C. State University, Raleigh, N. C.; August, 1965.

CONTENTS

PROJECT NO. 588-1.   SURFACE RECOMBINATION VELOCITY INVESTIGATIONS

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In the previous report (SDL-2-588), the variation of surface recombination velocity as a function of gamma irradiation for 100 ohm cm. n- and p-type silicon was reported. A study of the literature (Refs. 1, 2, and 3) shows that the models which have been used to explain the recombination of carrier pairs at the   surface are not adequate for the explanation of the observed variations, unless something other than a monotonic variation of the surface potential with irradiation is assumed. Since the flaw density varies linearly with gamma irradiation (Refs. 4 and 5) the monotonic variation appears to be a plausible assumption. In order to explain the results obtained in the above report, a new model for surface recombination velocity has been developed (Ref. 6).

Consider the equilibrium energy band structure of a semiconductor surface in the presence of surface states as shown in Figure 1. The equilibrium carrier densities can be expressed in terms of the difference of electron energies $E_F - E_i = q\phi$, where E_F is the Fermi level, and E_i is the Fermi level of an intrinsic semiconductor (approximately $E_g/2$),

Thus

$$n_0(x) = n_i \exp\left[\beta\phi(x)\right]$$
$$p_0(x) = n_i \exp\left[-\beta\phi(x)\right] \tag{1}$$

and at the surface

$$n_0(0) = n_{so} = n_i \exp\left[\beta\phi_s\right]$$
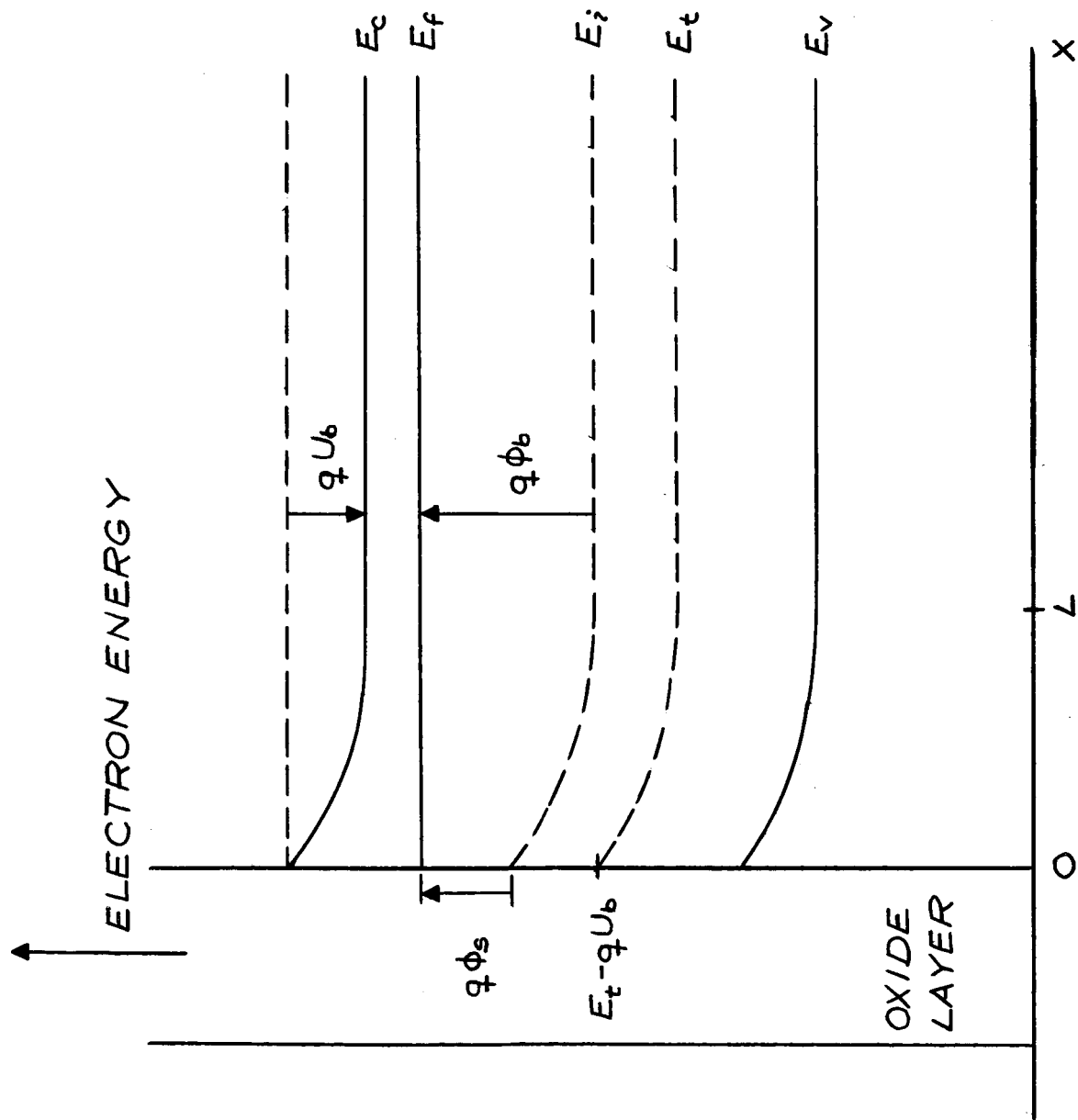$$p_0(0) = p_{so} = n_i \exp\left[-\beta\phi_s\right] \tag{2}$$

Figure 1. Equilibrium Energy Band Diagram for N-type Silicon with a surface Depletion Layer

Here $\beta = q/kT$. The recombination rate (number of recombining hole-electron pairs per unit time) can be expressed according to the Shockley-Read-Hall theory (Refs. 7 and 8) as

$$U(x) = \frac{N_t c_p c_n [n(x)p(x) - n_i^2]}{c_n [n(x) + n_1] + c_p [p(x) + p_1]} \qquad (3)$$

At $X = 0$ a parameter which is called the surface recombination velocity (because of its units, and because of the implication that a flux of either holes or electrons toward the surface can be represented by a velocity times a concentration) can be defined as

$$s = \frac{\text{Recombination Rate at } X = 0}{\text{Excess hole (or electron) concentration at } X = 0} \qquad (4)$$

In the previously mentioned models, S has been defined in terms of the excess hole (or electron) concentration at the edge of the space charge region ($x = L$ in Figure 1). This represents a "hybrid" relationship, and thus does not truly describe the rate of removal of carrier pairs at the surface. The true surface recombination velocity should be defined by Eq. (4) while realizing the important factors which determine the rate of arrival of carrier pairs at the surface.

The flux of carriers in a plane in the space charge region parallel to the surface can be written

$$f_p(x) = S_p(x) \overline{p}(x)$$
$$f_n(x) = S_n(x) \overline{n}(x) \qquad (5)$$

The requirement that the total current be zero imposes the condition that

$$f_p(x) = f_n(x) \qquad (6)$$

at all points in the space charge region. The assumption of quasi-charge neutrality in the bulk gives

$$f_p(L) = f_n(L). \qquad (7)$$

Then, from equating eq. (5)

$$\frac{S_n(0)}{S_p(0)} = \frac{\overline{P}(0)}{\overline{n}(0)} = \overline{P_s} / \overline{n_s} \qquad . \tag{8}$$

Invoking quasi-equilibrium between the bulk and the surface gives

$$p(0)n(0) = n_s p_s = p(L)n(L) \qquad . \tag{9}$$

Substituting equilibrium and excess concentrations into (9), assuming mass action and solving for n_s gives

$$\overline{n_s} = \frac{\overline{p}(L)\left[n_0(L)+p_0(L)+\overline{p}(L)\right] - \overline{p_s}n_0(L)}{p_{so} + \overline{p_s}} \tag{10}$$

and

$$\frac{S_n(0)}{S_p(0)} = \frac{\overline{p_s}\left[p_{so} + \overline{p_s}\right]}{\overline{p}(L)\left[n_0(L)+p_0(L)+\overline{p}(L)\right] - \overline{p_s}n_0(L)} \qquad . \tag{11}$$

At equilibrium there exists a potential barrier in the space charge region. Under injection this barrier changes, and the variation can be defined in terms of a voltage. The Boltzmann boundary conditions (Ref. 9) of p-n junction theory become

$$\overline{p_s} = p_{so}\left[e^{\upsilon} - 1\right]$$
$$\overline{p}(L) = p_0(L)\left[e^{\upsilon} - 1\right] \qquad . \tag{12}$$

Thus when $\upsilon = 0$, $\overline{p_s} = \overline{p}(L) = 0$. Substituting eq. (12) into (11) gives

$$\frac{S_n(0)}{S_p(0)} = \left[\frac{p_{so}}{p_0(L)}\right]^2 \qquad . \tag{13}$$

or using (1), (2), and (8),

$$\frac{S_n(0)}{S_p(0)} = \frac{\overline{p_s}}{\overline{n_s}} = \exp\left[-2\beta(\phi_s - \phi_b)\right]$$

or

$$\frac{S_n(0)}{S_p(0)} = \frac{\overline{p_s}}{\overline{n_s}} = \left(\frac{n_{bo}}{p_{bo}}\right)\exp(-2\beta\phi_s) \quad . \qquad (14)$$

Now at $x = 0$, (3) becomes

$$U_s = \frac{C_n C_p N_{ts}(n_s p_s - n_i^2)}{C_n(n_s + n_1) + C_p(p_s + p_1)} \quad . \qquad (15)$$

For simplicity assume $C_p = C_n = C$ and $n_1 = p_1 = n_i \ (E_t = E_i)$. Then

$$U_s = c N_{ts}\left[\frac{n_s p_s - n_i^2}{p_s + n_s + 2n_i}\right] \quad . \qquad (16)$$

In terms of equilibrium and excess concentrations at the surface

$$U_s = c N_{ts} \cdot \frac{\overline{p_s}\left(n_{so} + \frac{\overline{n_s}}{\overline{p_s}}\cdot p_{so} + \overline{n_s}\right)}{2n_i\left[\cosh\beta\phi_s + \frac{\overline{p_s}}{2n_i}(1 + \frac{\overline{n_s}}{\overline{p_s}}) + 1\right]} \quad . \qquad (17)$$

Assuming low level injection such that $\overline{n}_s$ will always be much less than either of the two terms in the numerator of (17),

$$U_s = c N_{ts} \frac{\overline{p_s}\left(n_{so} + \frac{\overline{n_s}}{\overline{p_s}}\cdot p_{so}\right)}{2n_i\left[\cosh\beta\phi_s + \frac{\overline{p_s}}{2n_i}(1 + \frac{\overline{n_s}}{\overline{p_s}}) + 1\right]} \quad . \qquad (18)$$

Then

$$S_p = \frac{c N_{ts}}{2} \cdot \frac{(1+\gamma)\exp(\beta\phi_s)}{\cosh\beta\phi_s + \overline{P}[\gamma\exp(2\beta\phi_s) + 1] + 1} \quad . \qquad (19)$$

where $\gamma = \left(\dfrac{p_{bo}}{n_{bo}}\right) = \left(\dfrac{p_{bo}}{n_i}\right)^2$ and $\bar{P} = \overline{P_s}/2n_i$

Thus s_p is a function of the surface potential, the bulk concentrations, and the injection level at the surface.

A similar expression can be derived for s_n by the same process, and is

$$s_n = \frac{cN_{ts}}{2} \cdot \frac{(1+\alpha)\exp(-\beta\phi_s)}{\cosh\beta\phi_s + \bar{N}[\alpha\exp(-2\beta\phi_s)+1]+1} \qquad (20)$$

where $\alpha = \left(\dfrac{n_{bo}}{p_{bo}}\right) = \left(\dfrac{n_{bo}}{n_i}\right)^2$ and $\bar{N} = \overline{n_s}/2n_i$

Note that s_p and s_n are anti-symmetrical in $\beta\phi_s$ for the same values of $\bar{N}$ and $\bar{P}$ and α and γ. Also note that $\bar{N}$ and $\bar{P}$ cannot be specified independently. Plots of s_p and s_n with the same values of $\bar{P}$ and $\bar{N}$ and γ and α are shown in fig. 2.

It is well known (Ref. 10) that, in a depletion region, there can be a significant contribution to hole and electron flow due to recombination-generation current in this region. This current is given by

$$J_u = q \int_0^L U(x)\,dx \qquad . \qquad (21)$$

Substituting (3)

$$J_u = q \int_0^L \frac{np - n_i^2}{\tau_{po}(n+n_1) + \tau_{no}(p+p_1)}\,dx \qquad (22)$$

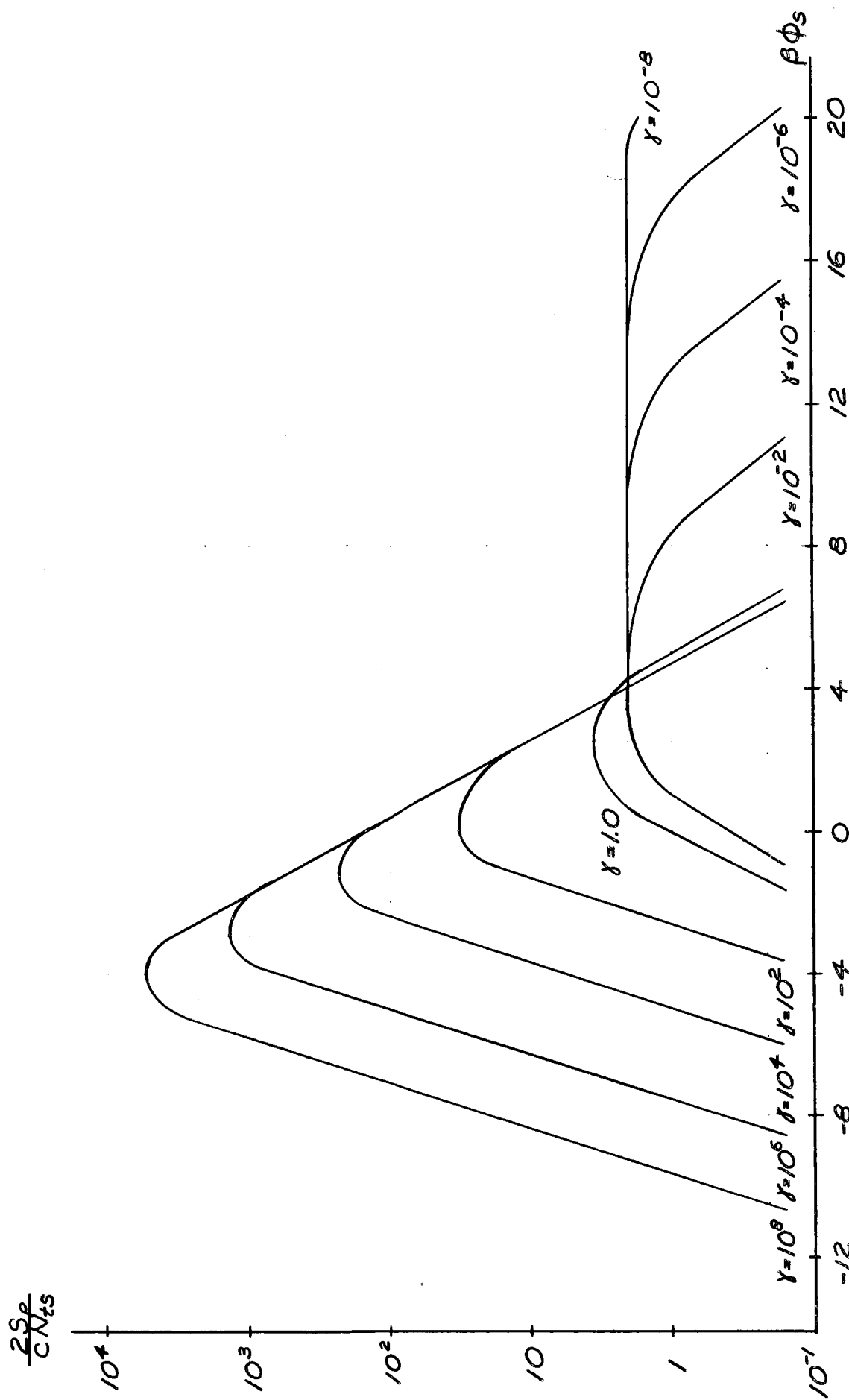where $\tau_{po} = 1/c_p N_t$ and $\tau_{no} = 1/c_n N_t$.

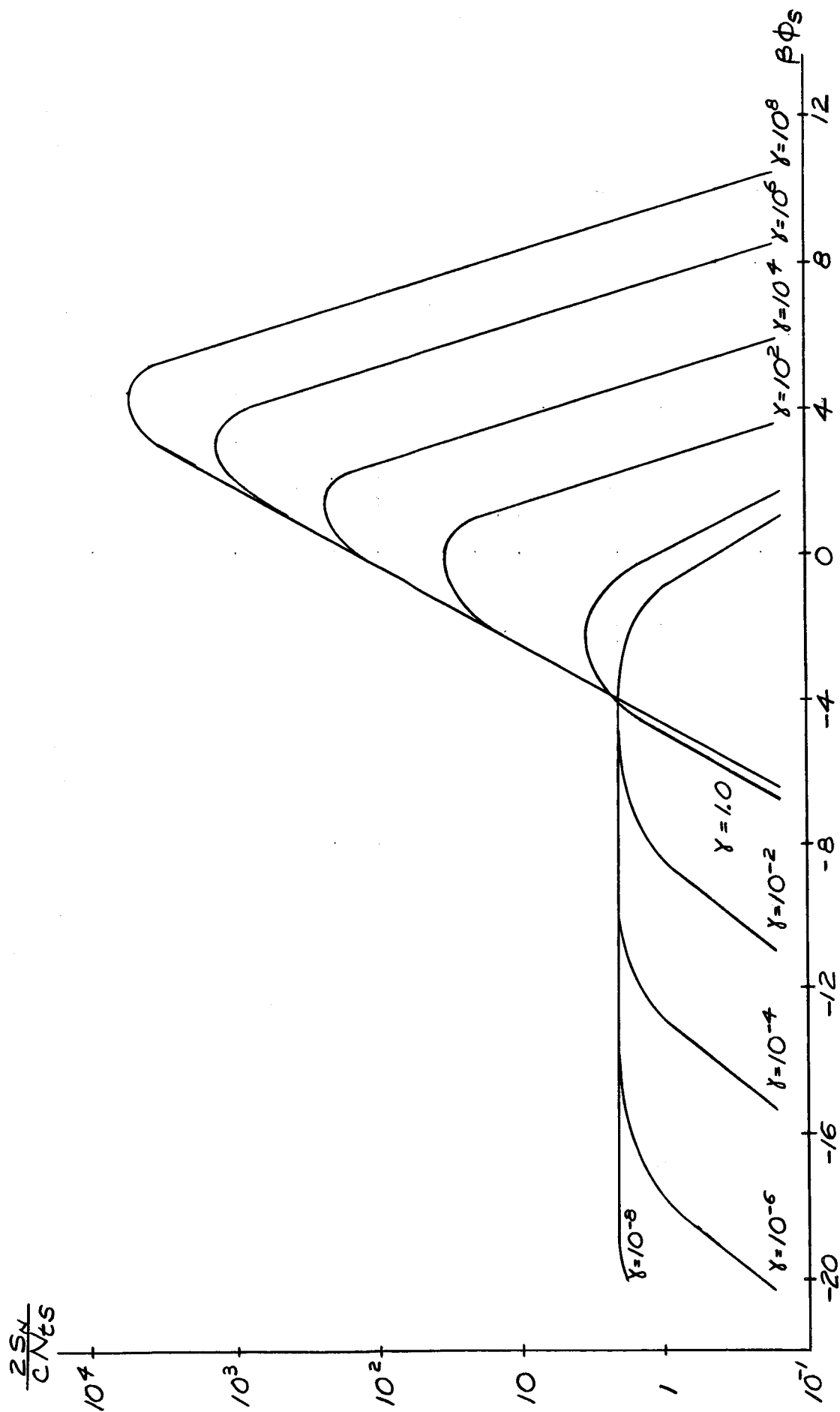Figure 2(a). S_p vs. $\beta\phi_s$ with p_o/n_o as a parameter.

Figure 2(b). S_n vs. $\beta \phi_s$ with n_o/p_o as a parameter.

Using an approximation for this integral (Ref. 11) and assuming low level injection, this current becomes

$$J_u = \frac{q L p_{bo} \bar{n}}{(\tau_{po} n_1 + \tau_{no} p_1) + (\tau_{po} + \tau_{no}) n_i} \qquad \cdot \qquad (23)$$

This current gives rise to an effective surface recombination velocity

$$J_u = q \bar{n} S_{eff} \qquad (24)$$

from which

$$S_{eff} = \frac{p_{bo} L(\beta \phi_s)}{2 n_i (\tau_{po} + \tau_{no})} \qquad (25)$$

by assuming $n_1 = p_1 = n_i$.

It appears that this contribution to surface recombination velocity would be important in a strong depletion region or an inversion region (Ref. 12). Valdes shows that in this type of surface layer, $L(\beta \phi_s)$ vs. ϕ_s would be nearly parabolic. His analysis breaks down, however, when the surface charge becomes large enough so that the density of mobile carriers in the surface layer becomes comparable to the density of chemical impurities.

These two contributions to surface recombination velocity are enough to explain the observed variation of s with gamma irradiation.

First, it will be assumed that irradiation always causes the bands to bend upward in both n- and p- type material. Since the samples are irradiated in argon, the pre-irradiated surface should still have the same conductivity type as the bulk, although the presence of ozone in the Gamma Cell could tend to produce a p-type surface (Ref. 13). Also, it is to be expected that the measured surface recombination velocity will be the minority carrier value (i.e., s_p in n-type material) since the mathematical solution is given in terms of minority carriers.
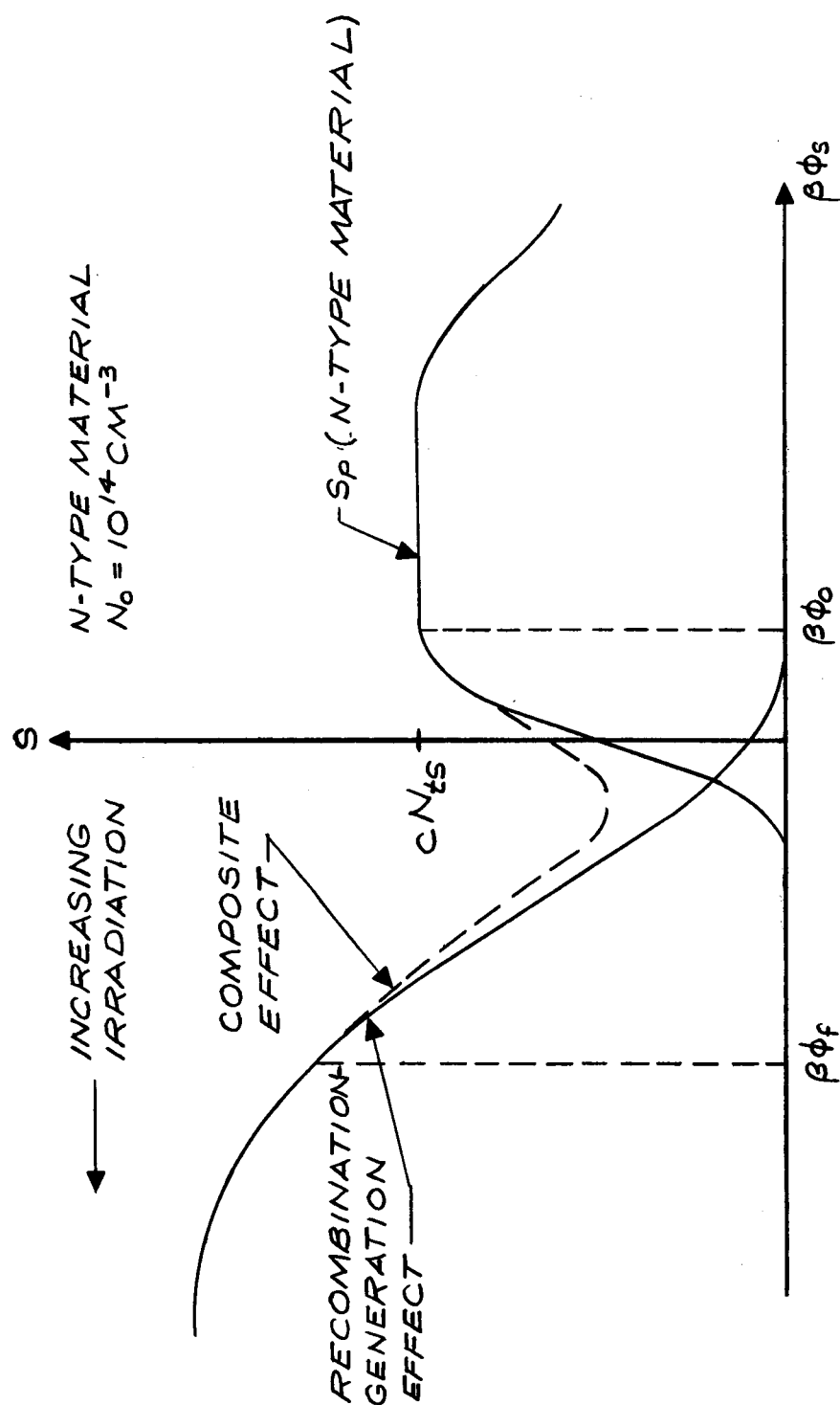
Figure 3(b). Predicted Variation of Surface Recombination Velocity as a Function of Co^{60} Gamma Dosage in N-type Silicon.
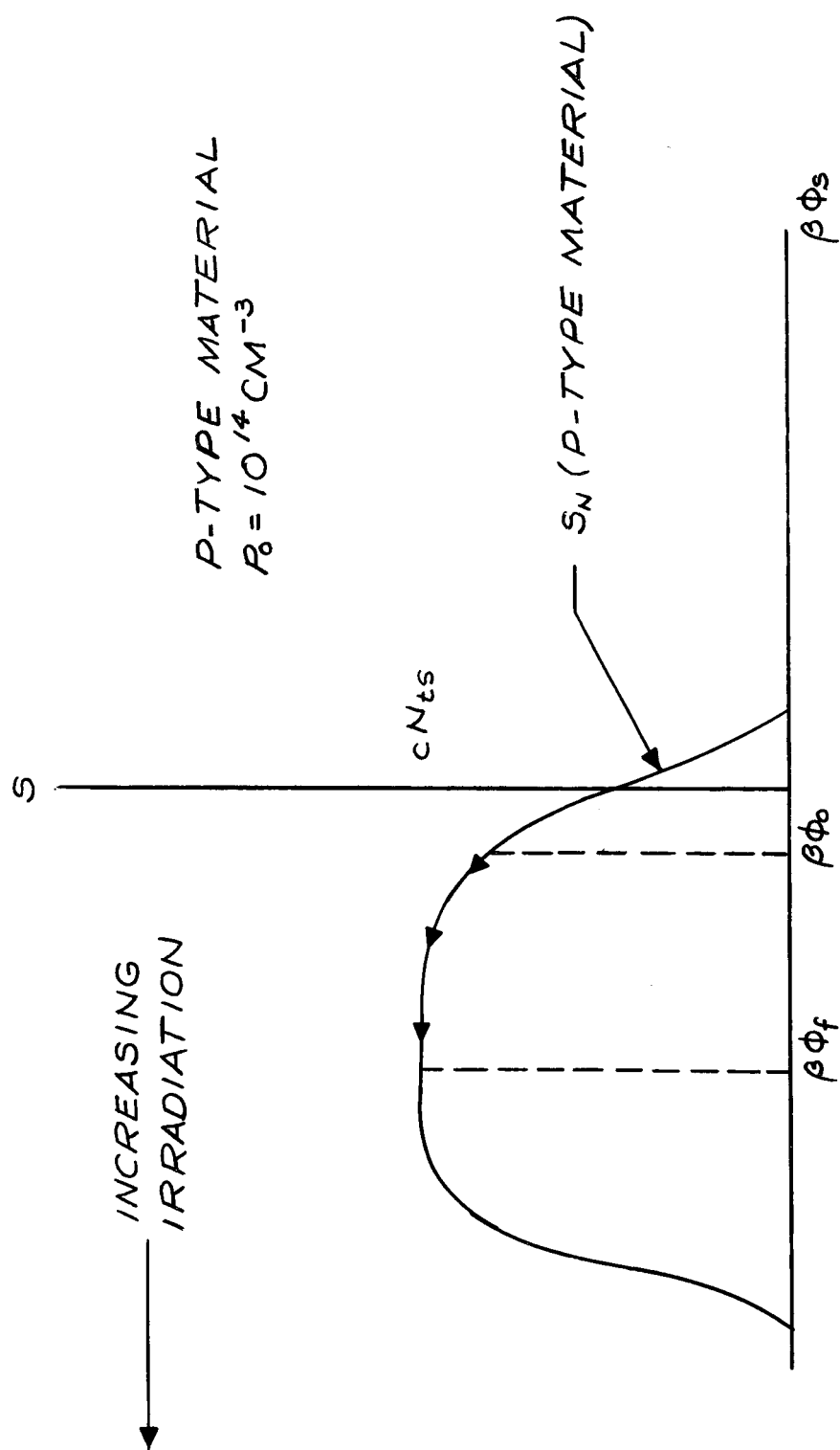
N-TYPE MATERIAL
$N_0 = 10^{14} CM^{-3}$

S_P (N-TYPE MATERIAL)

S

cN_{ts}

$\beta\phi_0$

$\beta\phi_s$

$\beta\phi_f$

INCREASING IRRADIATION

COMPOSITE EFFECT

RECOMBINATION GENERATION EFFECT

Figure 3(a). Predicted Variation of Surface Recombination Velocity as a Function of Co^{60} Gamma Dosage for p-type Silicon.

Now, for p-type material the variation in surface potential will be small, assuming that the surface will not become degenerate. The surface potential is negative initially and becomes more negative as the sample is irradiated, according to the above assumptions. The surface velocity becomes saturated at the valve cN_{ts} as shown in Figure 3(a), which is drawn for 100 ohm cm material.

In n-type material an inversion layer will be produced and the recombination effect will then become dominant. Figure 3(b) shows the expected variations of surface potential for 100 ohm cm n-type material.

In the latter part of this report period, work was begun on the investigation of the influence of gamma irradiation on passivated silicon surfaces ($Si - Si O_2$ interfaces). A set of n- and p-type samples were prepared, and the thin filaments were mechanically polished. Then, they were oxidized in a steam atmosphere at $1000^{\circ}C$ for 30 minutes to produce an oxide thickness of approximately $2500^{\circ}A$. The bulk samples were oxidized also, in order that any bulk lifetime variations due to heat treatment could be accounted for. As it turned out, this heat treatment had a very drastic effect on the bulk lifetime in n-type material, with a somewhat less drastic reduction for p-type material. Table I shows the variation in bulk lifetime for four n-type and 3 p-type samples.

TABLE I

SAMPLE	(before oxidation)	(after oxidation)
N-1	513 μs	4.1 μs
N-2	642 μs	4.1 μs
N-3	393 μs	4.3 μs
N-4	245 μs	4.6 μs
P-1	445 μs	37.5 μs
P-2	330 μs	38.0 μs
P-3	468 μs	39.0 μs

Due to this reduction in bulk lifetime, the filament lifetime for all thin samples was diminished to a value which reduced the accuracy for measurement with the method of photo-conductive decay. While the influence of heat treatments on lifetime has long been recognized (Ref. 14), the mechanisms of this reduction are admittedly complex and not well understood. This problem poses an interesting sidelight to the original plan of investigation. Thus, while variations of lifetime and other bulk parameters have been reported for various fabrication techniques, no known variations of surface recombination velocity have been found in the literature. While it is realized that lifetime and surface velocity are intimately related, further investigations into the variation of surface velocity with fabrication techniques appear to be in order.

One step in the further investigations of surface velocity has been taken, with samples being prepared to be sent to RCA for a special low temperature ($300^{\circ}C$) oxidation process which has been developed at their Princeton, New Jersey facilities.

List of Symbols

$\mathcal{T}_f$ - filament lifetime, sec.

$\mathcal{T}_b$ - bulk minority carrier lifetime, sec.

$\mathcal{T}_s$ - surface lifetime, sec.

s - surface recombination velocity, cm/sec.

E_t - flaw energy level in forbidden gap, ev.

E_c - conduction band edge, ev.

E_f - Fermi level, ev.

E_i - Intrinsic Fermi level, ev.

E_v - Valence band edge, ev.

p, n, - total (equilibrium plus excess) hole and electron concentrations, cm^{-3}

p_o, n_o - equilibrium hole and electron concentrations, cm^{-3}

$\bar{p}$, $\bar{n}$, - excess hole and electron concentrations, cm^{-3}

p_1, n_1 - hole and electron concentrations when $E_t = E_i$, cm^{-3}

c_n, c_p - mean capture co-efficients, $cm^3 sec^{-1}$.

n_i - hole and electron concentration in an intrinsic semiconductor, cm^{-3}.

f_p, f_n - hole and electron fluxes, $cm^{-2} sec^{-1}$.

N_t - net trap density, cm^{-3}

N_{ts} - net surface trap density, cm^{-2}

J_u - recombination-generation current, amp cm^{-2}.

ϕ_B - bulk electrochemical potential, volts.

ϕ_s - surface electrochemical potential, volts.

q - electronic charge, coulombs.

qV_b - barrier height at the surface, ev.

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PROJECT NO. 588-2. SURFACE STUDIES ON M. O. S. CAPACITORS

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The study of surface phenomena was responsible for the invention of the bipolar transistor by Brattain and Bardeen. Since the mechanism of operation of this transistor is of a bulk nature, surface studies were forced to assume a position of lesser importance with respect to bulk studies. It was not until interest was shown in metal-oxide-semiconductor transistors that surface studies again came into the foreground, since the operational mechanism of these transistors is of a surface nature.

Unfortunately the current-voltage characteristics and thus the device parameters of these transistors are of a variable nature. The variation noted is dependent upon time, temperature, humidity, radiation, etc. It is hoped that these problems of device parameter variation will be more readily solved by a more firm understanding of the material processes dependent upon the above conditions.

Many authors have investigated surface state densities on silicon.[1,2,3,4,5] It is the purpose of this section to report on surface density studies as a function of gamma radiation.

The following method was used for the fabrication of MOS devices on which surface state density measurements were made: 93 ohm cm p-type substrates were wafered from a $\langle 111 \rangle$ Czochralski pulled ingot. These wafers were mechanically lapped and chemically etched to produce a mirror-like surface. After being carefully cleaned the wafers were thermally oxidized in a steam atmosphere at $1000^\circ C$. This oxidation produced a very strong n-type surface.[6] A metal evaporation mask was used to produce a series of circular aluminum pads on the oxide. Each pad constituted the metal electrode of an MOS capacitor as shown in Figure 1. Silicon dioxide served as the dielectric and was approximately 4300 Å thick.
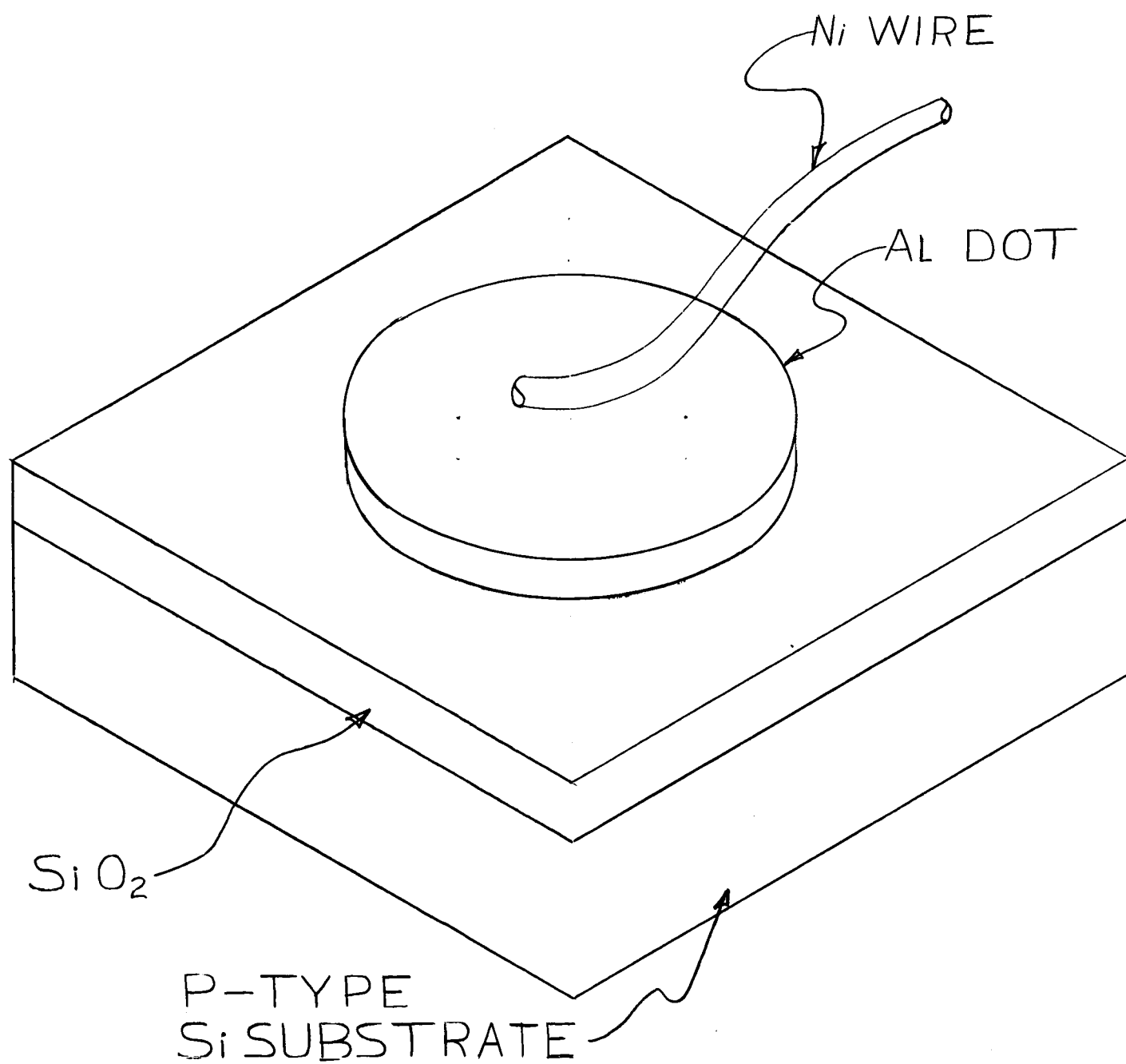
Figure 1.   A typical MOS capacitor fabricated on p-type silicon.

A General-Radio type 716-C capacitance bridge was used along with auxiliary biasing equipment to obtain curves of capacitance versus bias voltage at various frequencies. The circuit is shown in Figure 2, while Figure 3 gives typical capacitance-bias curves for various frequencies.

The method of obtaining surface state density as of function of energy is that of Zaininger.[4,5] A brief explanation of this method and the mathematical derivation will be given for completeness.

The following relation can be written for the device shown in Figure 1.

$$D_{ox} = \epsilon_{ox} E_{ox} = \frac{\epsilon_{ox}}{W_{ox}} (V - \psi_s) = C_{ox} (V - \psi_s) = - Q_{TOT} \quad (1)$$

where ϵ_{ox} is the oxide permittivity, ψ_s is the surface potential of the semiconductor substrate, and C_{ox} is the oxide capacitance per unit area. If capacitance is defined in the incremental fashion the following expression obtains:

$$C \equiv - \frac{d Q_{TOT}}{dV} = C_{ox} \left(1 - \frac{d \psi_s}{dV} \right) \quad (2)$$

From this expression it can be seen that the device capacitance is determined almost completely by the ability of the surface potential to follow an applied voltage. Two extreme cases are now apparent.

CASE I: If a strong surface density is present a small change in bias voltage will cause a very small change in surface potential such that $\frac{d \psi_s}{dV} \approx 0$ Therefore, $C \simeq C_{ox}$.

CASE II: If the surface is essentially depleted of carriers a small change in applied voltage will cause nearly the same change in surface potential. Thus, $\frac{d \psi_s}{dV} \lesssim 1$, and C is very small.

From the potential band diagram of figure 4 one can see that Q_{TOT} is composed of charge in surface states and charge in the semiconductor due entirely to band bending. Thus:
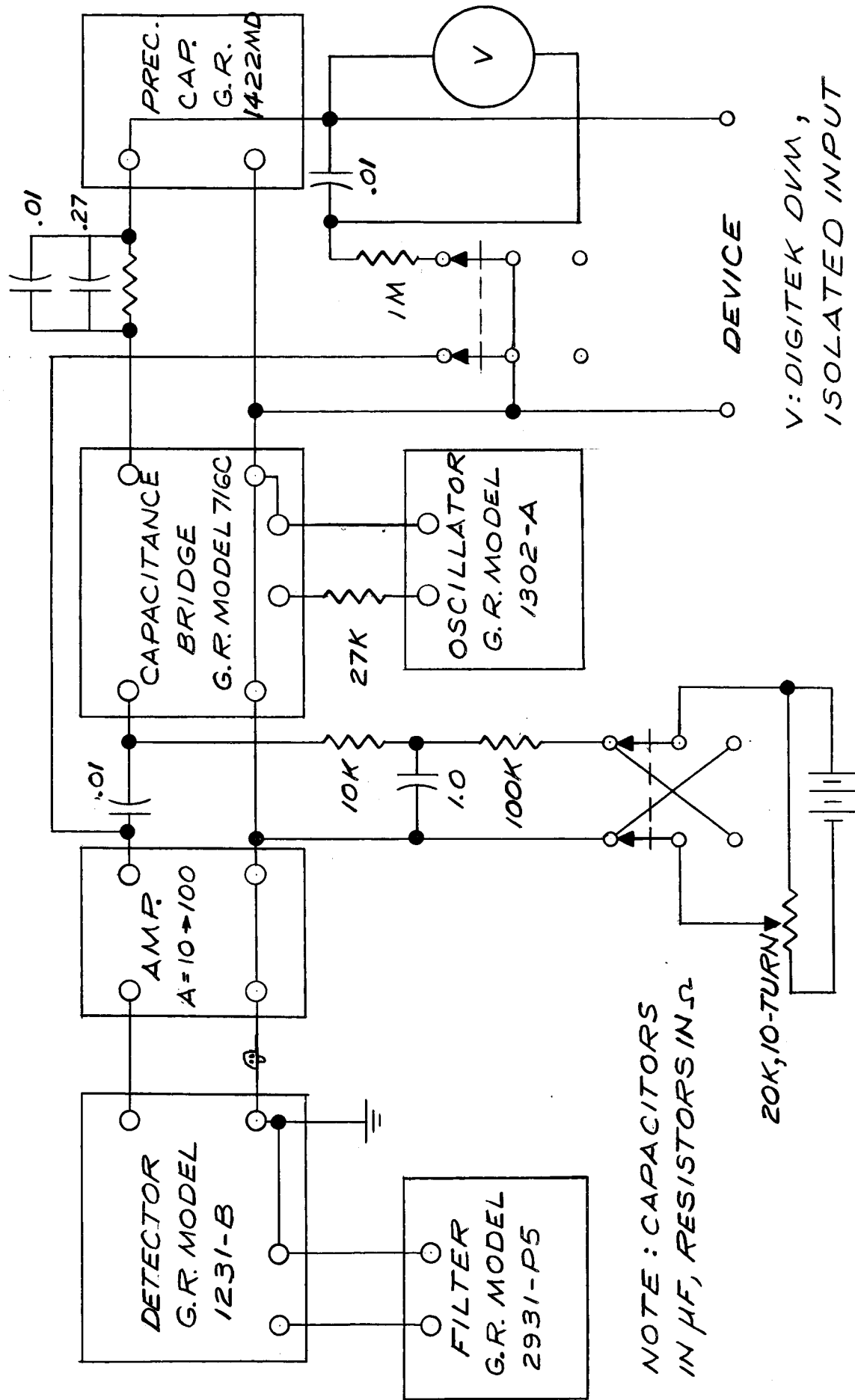
$$Q_{TOT} = Q_{ss} + Q_{sc} \quad (3)$$

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Figure 2. Diagram of circuitry used for capacitance versus bias voltage measurements.

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CAPACITANCE (PFD)

110
100
90
80
70
60
50
40

f=1 KHZ
f=10KHZ
f=100KHZ

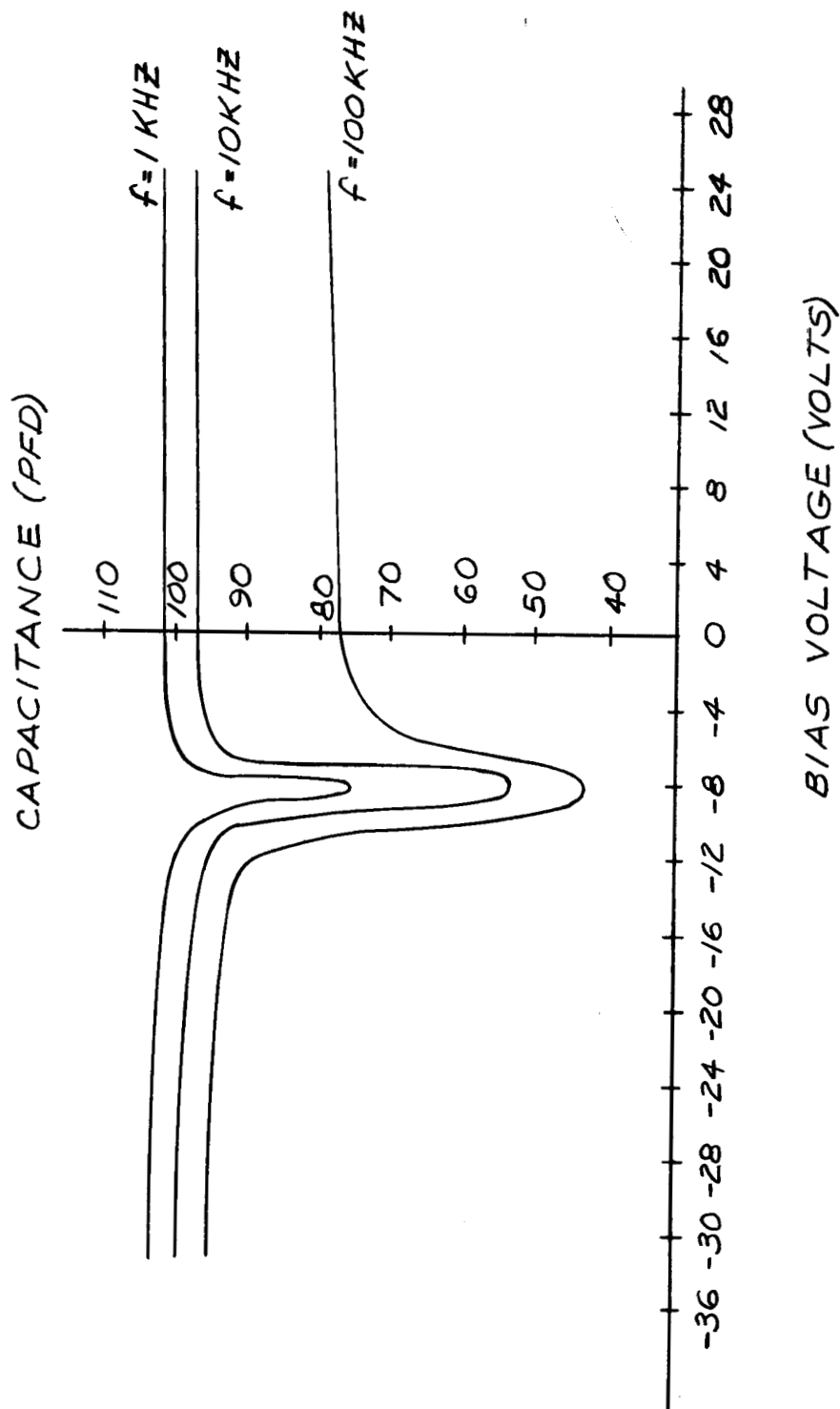-36 -30 -28 -24 -20 -16 -12 -8 -4 0 4 8 12 16 20 24 28

BIAS VOLTAGE (VOLTS)

Figure 3.

MOS Capacitance versus bias voltage for different frequencies.
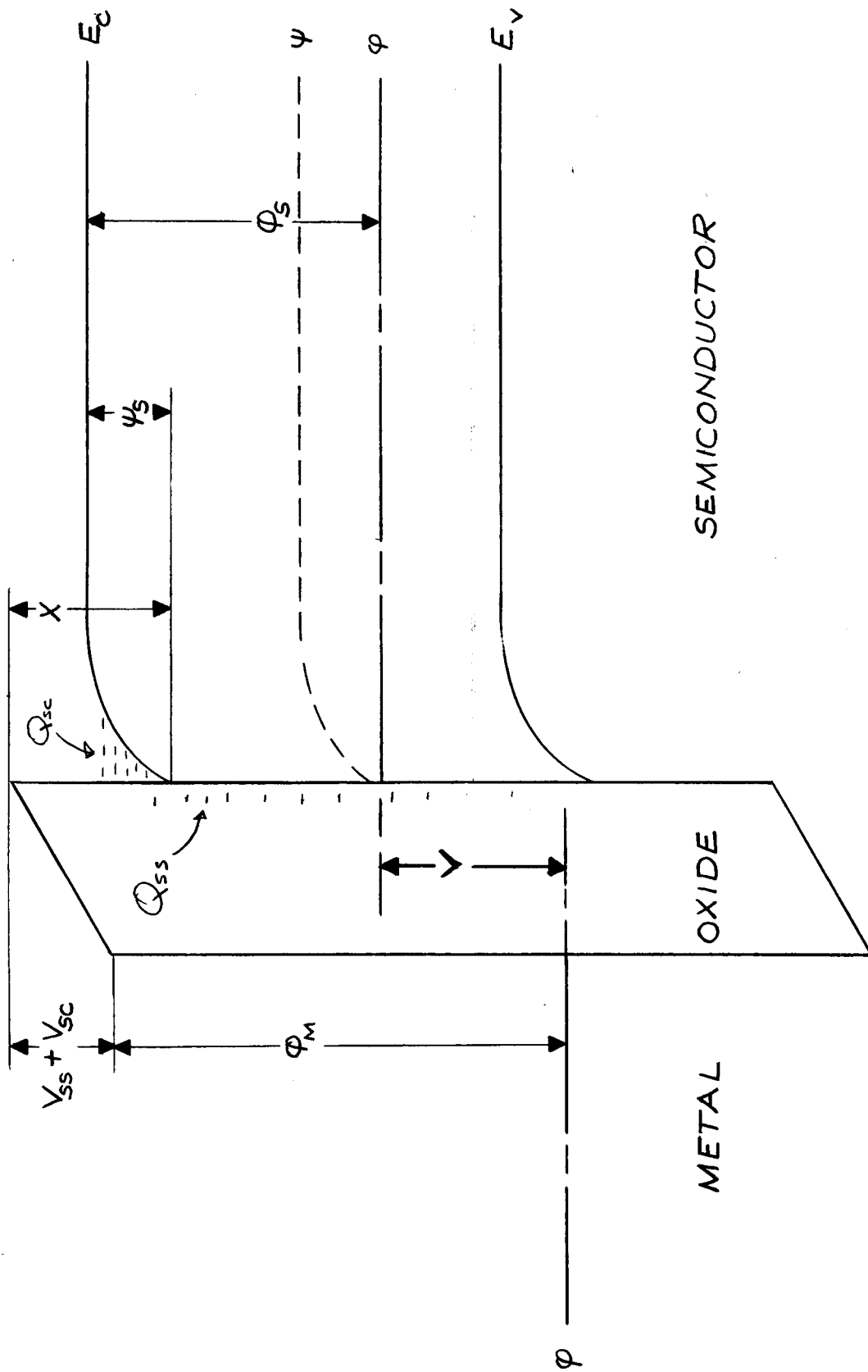
Figure 4.

Energy band diagram for an MOS capacitor with applied voltage V.

and $C_{ox} (V - \psi_s) = - Q_{ss} - Q_{sc}$. It is now possible to define two new potentials as follows:

$$V = \psi_s + V_{ss} + V_{sc} \qquad (4)$$

where

$$V_{ss} = - \frac{Q_{ss}}{C_{ox}} \qquad (5)$$

and

$$V_{sc} = - \frac{Q_{sc}}{C_{ox}} \qquad (6)$$

V_{sc} is completely determined by the substrate surface potential whereas V_{ss} is dependent on both V and ψ_s. Capacitance can thus be written:

$$C = C_{ox} \left(1 - \frac{d\psi_s}{dV}\right) \qquad (7)$$

$$= C_{ox} \left[1 - \frac{1}{dV/d\psi_s}\right]$$

$$= C_{ox} \left[\frac{\frac{dV_{ss}}{d\psi_s} + \frac{dV_{sc}}{d\psi_s}}{1 + \frac{dV_{ss}}{d\psi_s} + \frac{dV_{sc}}{d\psi_s}}\right] . \qquad (8)$$

Now if the frequency of the applied signal is relatively high (greater than 10^3 cps) $\frac{dV_{ss}}{d\psi_s}$ will be essentially zero since the surface state response time will be greater than a period of that signal. Hence

$$C = C_{ox} \left[\frac{\frac{dV_{sc}}{d\psi_s}}{1 + \frac{dV_{sc}}{d\psi_s}}\right] \qquad (9)$$

or

$$\frac{dV_{sc}}{d\psi_s}\bigg|_V = \frac{C(V)}{C_{ox} - C(V)} \qquad (10)$$

If one has a curve of C versus V for an arbitrarily high frequency one can obtain a corresponding curve of $\frac{dV_{sc}}{d\psi_s}$ versus V.

A curve relating $\dfrac{dV_{sc}}{d\psi_s}$ and ψ_s is now necessary in order to find ψ_s vs. V. It is possible to calculate $dV_{sc}/d\psi_s$ vs. ψ_s by utilizing Poisson's and Gauss's equations. Poisson's equation for a p-type semiconductor with an acceptor concentration N_A is

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\epsilon_s}\left[\rho - n + N_D^+ - N_A^-\right] \tag{11}$$

$$= -\frac{q}{\epsilon_s}\left[N_A\left(e^{-\beta\psi} - 1\right) - n_o\left(e^{\beta\psi} - 1\right)\right] \tag{12}$$

where

$$\rho = N_A\, e^{-\beta\psi} \tag{13}$$

$$n = n_o\, e^{\beta\psi} \tag{14}$$

$$N_D^+ = n_o \tag{15}$$

$$N_A^- = N_A \tag{16}$$

$$\beta = \frac{q}{kT} \tag{17}$$

and complete ionization of donors and acceptors is assumed. If we let $\dfrac{d\psi}{dx} = V$

$$\frac{d^2\psi}{dx^2} = \frac{dV}{dx} = \frac{dV}{d\psi}\frac{d\psi}{dx} = V\frac{dV}{d\psi} \tag{18}$$

thus

$$\int_0^V V\,dV = -\frac{q}{\epsilon_s}\int_0^{\psi_s}\left[N_A\left(e^{-\beta\psi} - 1\right) - n_o\left(e^{\beta\psi} - 1\right)\right]d\psi \tag{19}$$

$$\frac{V^2}{2} = -\frac{q}{\epsilon_s}\left[\psi_s\left(N_A - n_o\right) + N_A\left(\frac{kT}{q}\right)\left(e^{-\beta\psi} - 1\right) + n_o\left(\frac{kT}{q}\right)\left(e^{\beta\psi} + 1\right)\right] \tag{20}$$

$$\frac{d\psi}{dx} = \pm \sqrt{\frac{2N_a kT}{\epsilon_s}} \left(\beta\psi_s - 1 + e^{-\beta\psi_s} + \frac{n_o}{N_A}\left(e^{\beta\psi_s} - 1 - \beta\psi_s\right) \right)^{1/2} \tag{21}$$

But

$$E_s = - \frac{d\psi}{dx}\Big|_{\psi = \psi_s} \tag{22}$$

and since

$$E_{ox}\,\epsilon_{ox} = E_s\,\epsilon_s \tag{23}$$

$$E_{ox} = \frac{\epsilon_s}{\epsilon_{ox}} \sqrt{\frac{2N_a kT}{\epsilon_s}} \left(\beta\psi_s - 1 + e^{-\beta\psi_s} + \frac{n_o}{N_A}\left(e^{\beta\psi_s} - 1 - \beta\psi_s\right) \right)^{1/2} \tag{24}$$

$$V_{sc} = \pm 2\left(\frac{kT}{q}\right)\left(\frac{\epsilon_s}{\epsilon_{ox}}\right)\left(\frac{W_{ox}}{L_s}\right)\left[\beta\psi_s - 1 + e^{-\beta\psi_s} + \frac{n_o}{N_A}\left(e^{\beta\psi} - 1 - \beta\psi_s\right) \right]^{1/2} \tag{25}$$

where

$$L_s = \left[\frac{2kT\,\epsilon_s}{q^2 N_A} \right]^{1/2} \tag{26}$$

thus

$$\frac{dV_{sc}}{d\psi_s} = \pm \left(\frac{\epsilon_s}{\epsilon_{ox}}\right)\left(\frac{W_{ox}}{L_s}\right) \left\{ \frac{1 - e^{-\beta\psi_s} + \frac{n_o}{N_A}\left(e^{\beta\psi_s} - 1\right)}{\left[\beta\psi_s - 1 + e^{-\beta\psi_s} + \frac{n_o}{N_A}\left(e^{\beta\psi_s} - 1 - \beta\psi_s\right) \right]^{1/2}} \right\} \tag{27}$$

The previously mentioned curve of $\frac{dV_{sc}}{d\psi_s}$ vs V will have a minimum for the same value of V as does the C vs. V curve. The value of $\frac{dV_{sc}}{d\psi_s}$ at this minimum must correspond exactly to that of the $\frac{dV_{sc}}{d\psi_s}$ vs ψ_s relation above. Thus, the correct value of N_A at the surface must be chosen in (27) in order to prevent a discontinuity in surface potential vs. applied voltage. The value of N_A is found by means of a computer program.

Since ψ_s vs V has now been obtained a look at the band diagram of figure 4 will reveal

$$V = \phi_m + V_{sc} + V_{ss} - x - \phi_s + \psi_s \tag{28}$$

If

$$\phi_m = \chi + \phi_s \tag{29}$$

the following equation would obtain

$$V = V_{sc} + V_{ss} + \psi_s \tag{30}$$

Once V_{ss} is obtained N_{ss} vs ψ is gotten by a simple differentiation. V_{sc} must now be determined. Equation (25) gives the desired relation. Thus equation (30) can now be solved for V_{ss} vs. ψ_s. A computer program was written to solve the above problem and print out V, V_{sc}, ψ_s, V_{ss}. A curve of V_{ss} vs ψ_s was then plotted, smoothed out, and differentiated.

Since

$$\frac{d V_{ss}}{d \psi_s} = \frac{1}{C_{ox}} \left(\frac{d Q_{ss}}{d \psi_s} \right) = \frac{q}{C_{ox}} \left(\frac{d N_{ss}}{d \psi_s} \right) = \frac{q}{\epsilon_{ox}} N'_{ss} \tag{31}$$

then

$$N'_{ss}(\psi) = \frac{\epsilon_{ox}}{q} \frac{d V_{ss}}{d \psi_s} \tag{32}$$

Figure 5 exhibits curves of C versus V for various values of gamma radiation. Figure 6 bears the corresponding curves of surface state density as a function of surface potential for the same values of gamma radiation. It can be seen from curves 3, 4, and 5, that trap levels seem to be created by a certain amount of radiation and destroyed by any further irradiation.

Surface potential for zero bias can be readily calculated by knowing C_{ox}, C(0) and C_{min}. The value of $\left. \frac{d V_{sc}}{d \psi_s} \right|_{MIN}$ is calculated and the value of N_A adjusted in (27) in order that the minima be coincident. The value of $\left. \frac{d V_{sc}}{d \psi_s} \right|_{zero\ bias}$ is then calculated and the corresponding values of $\frac{d V_{sc}}{d \psi_s}$ and ψ_s are obtained from (22) by means of a computer program. Figure 7 illustrates $\left. \psi_s \right|_{zero\ bias}$ as a function of irradiation.
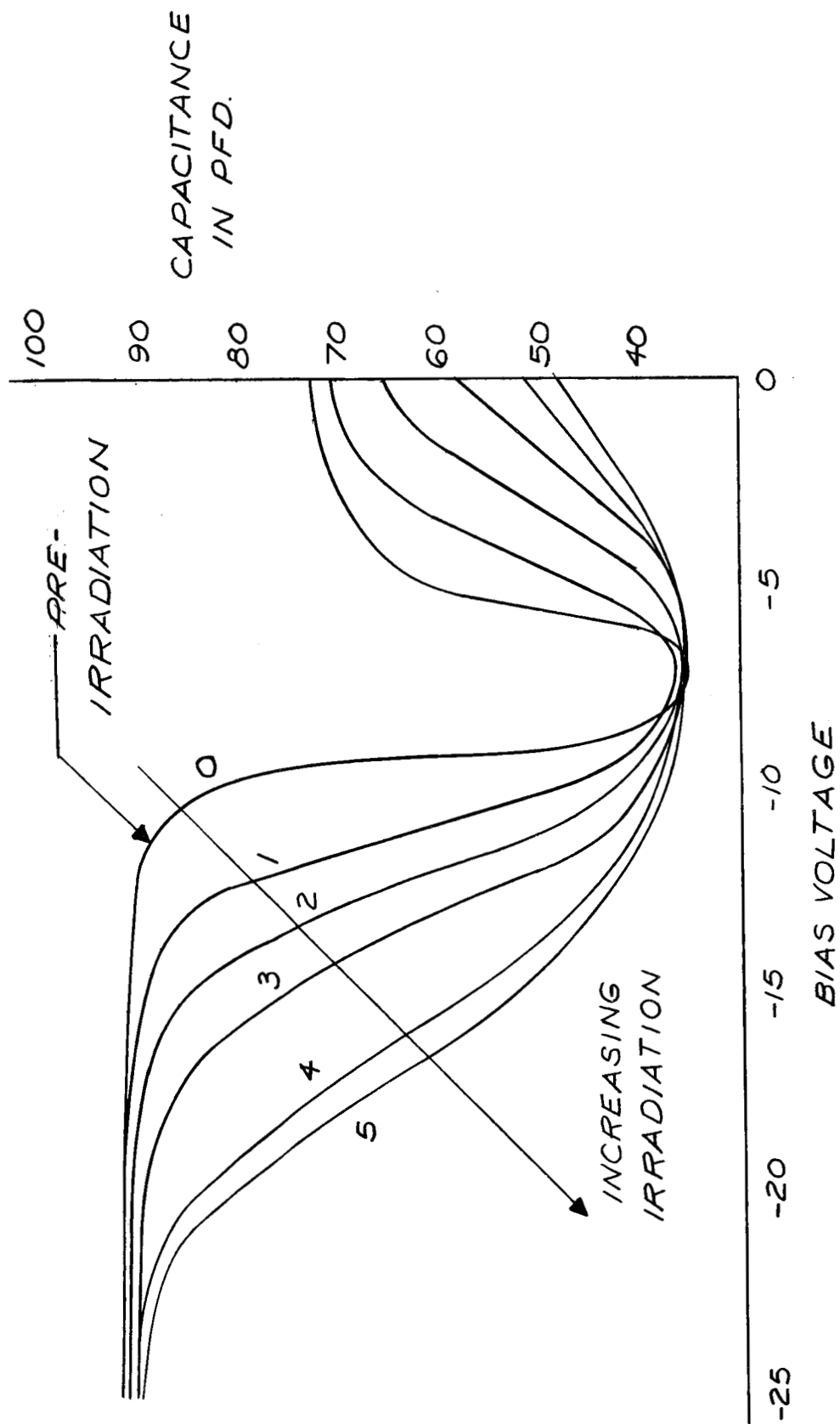
Figure 5. MOS capacitance versus bias voltage as a function of irradiation.
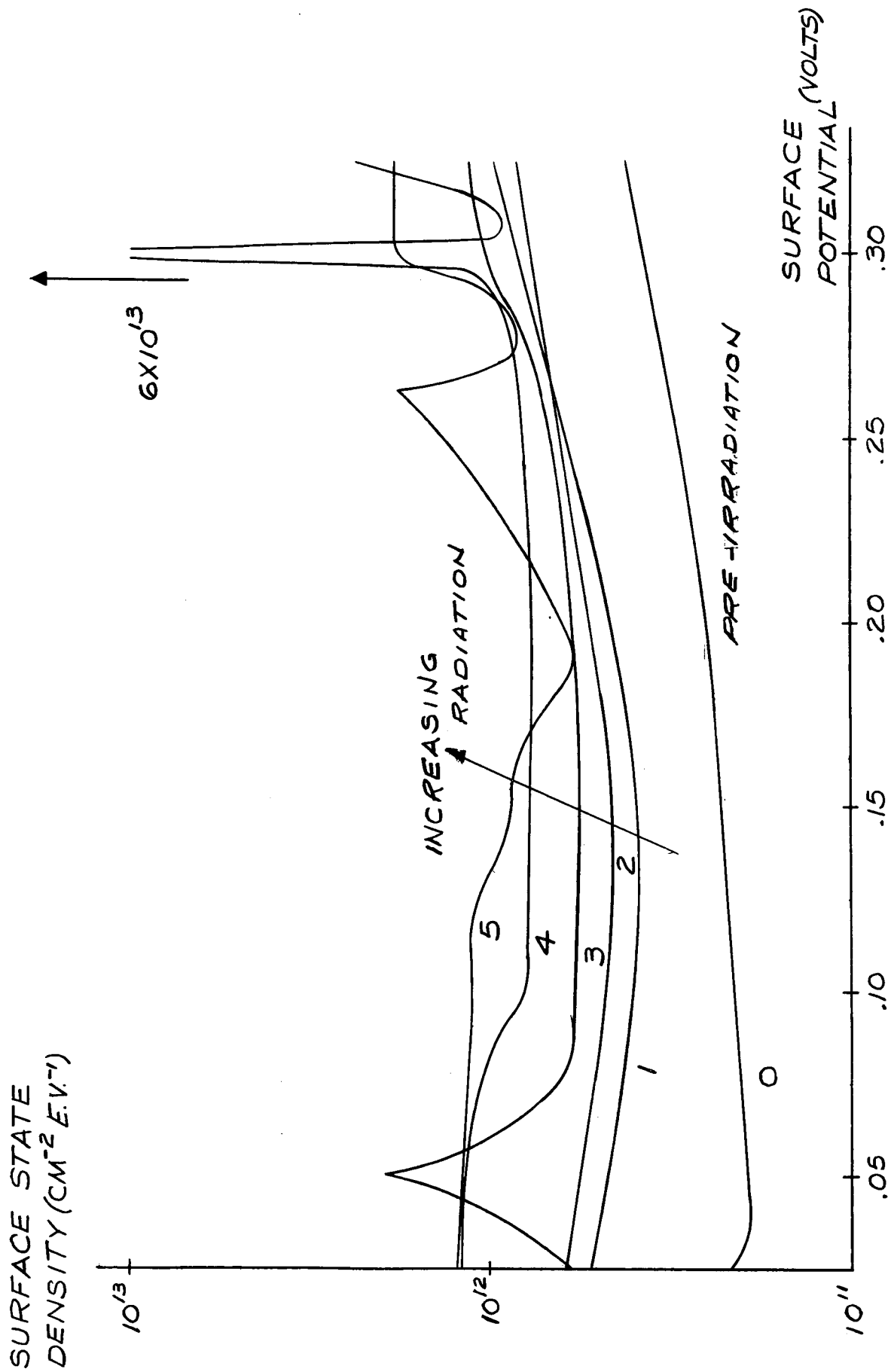
Figure 6.

Surface state density versus surface potential as a function of radiation. Preirradiation through fifth irradiation.
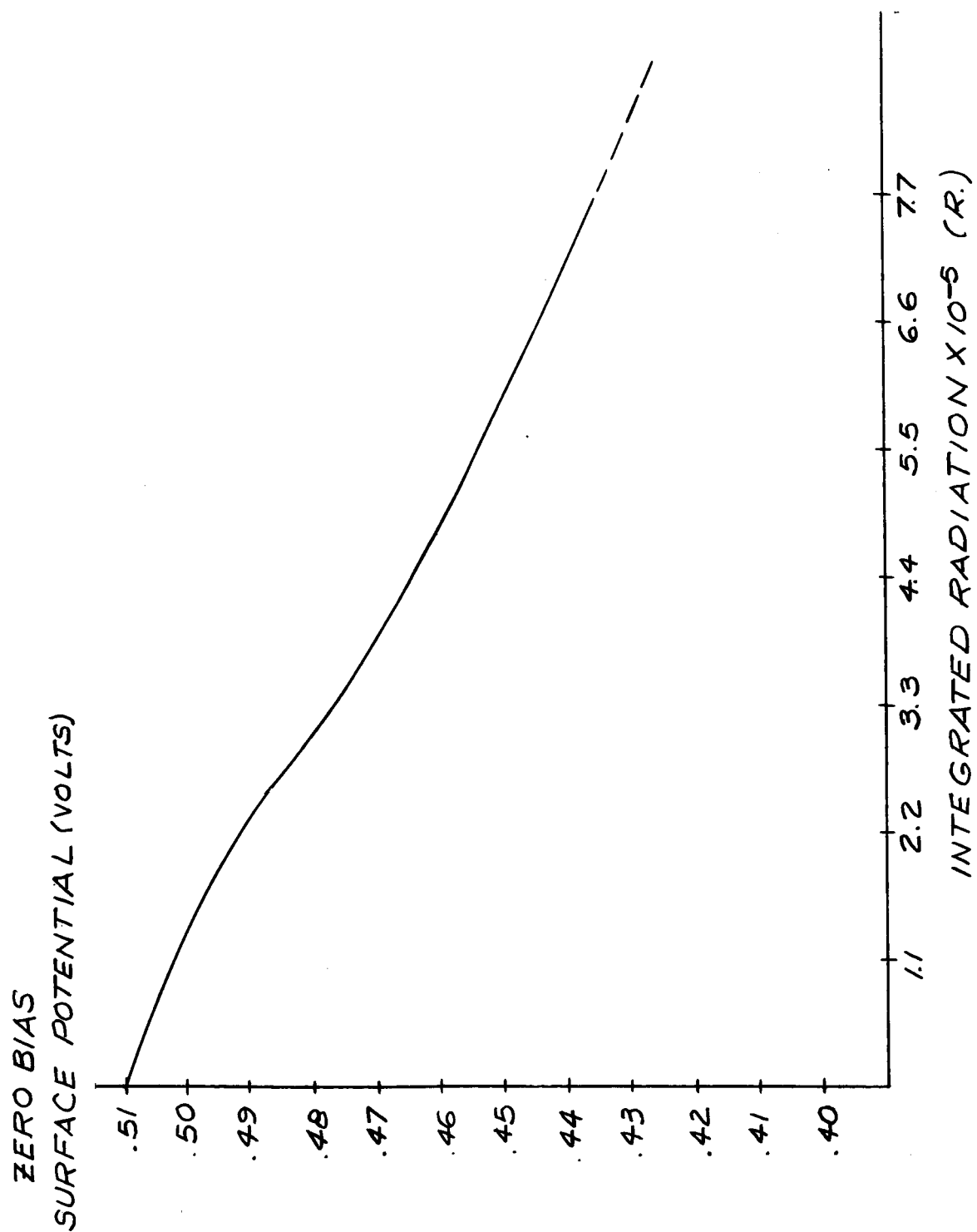
Figure 7.
Zero bias surface potential as a function of integrated radiation.

The future plans for this project call for fabrication of devices on both p-and n-type silicon. These devices will be irradiated in one quarter hour exposures and capacitance versus bias data will be taken in order to calculate surface state densities. Smaller exposure times will be used since these newly introduced levels can apparently be anihilated by gamma radiation. Surface potential for zero bias as a function of irradiation will also be the subject of extensive study.

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PROJECT NO. 588-3. MEASUREMENT OF SURFACE RECOMBINATION VELOCITY AS A FUNCTION
OF SURFACE POTENTIAL. (NEW PROJECT)

STAFF: F. J. MORRIS AND R. W. LADE

The objective of this project is to determine experimentally the effects
of surface potential on the surface recombination velocity of an oxide-silicon
surface and its variation with gamma radiation. A model will then be made to
explain these variations.

The measuring technique will be the following:
A method of diffusing a high resistivity region into a low resistivity silicon
substrate will first be perfected. It is also required that the depth of the
diffusion be on the order of 0.5 mils. This will involve a two-step diffusion
using either boron tribromide or phosphene gas. After a p-n junction with
the above-mentioned characteristics has been built, an oxide will be grown
over the diffused layer. A semi-transparent aluminum film will then be
evaporated over the oxide. The aluminum film will be thick enough to have
sufficiently low resistance. By masking and etching at the proper time,
contacts will be made to the substrate, diffused region, and aluminum gate.
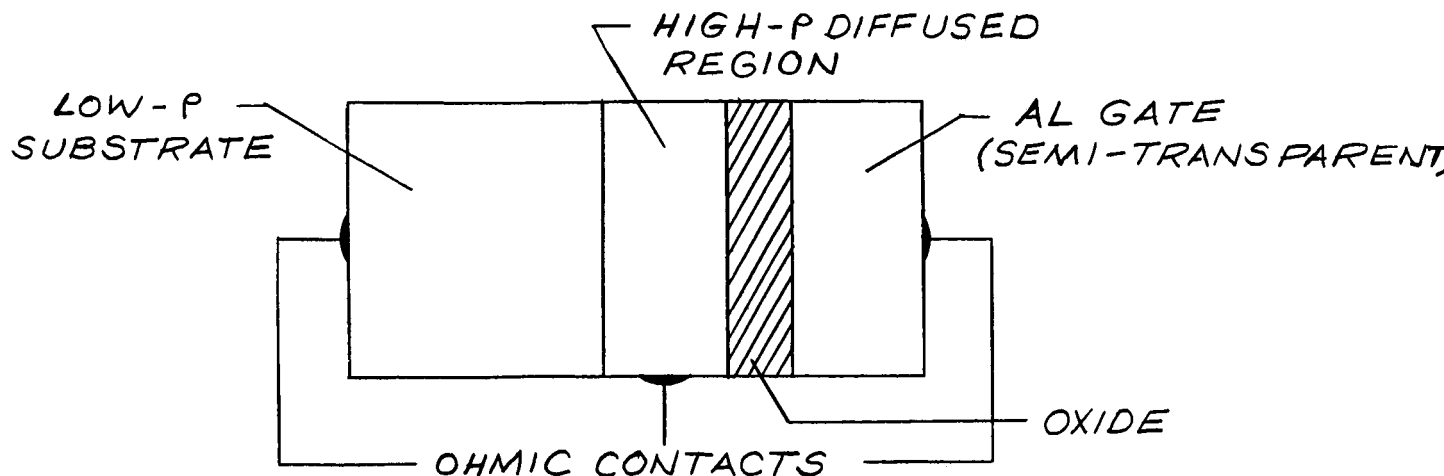See Figure 1 below:

Figure 1. Proposed device for measuring surface recombination
velocity.

By focusing an ultra-violet light source on the aluminum gate, the p-n junction will act as a solar cell. The short circuit current of the solar cell is a function of the surface recombination velocity of the silicon-oxide interface. By measuring the short circuit current for a fixed light intensity and varying the potential on the gate, the variation of the surface recombination velocity, with surface potential can be determined.

A second independent method for determining this variation is by measuring the reverse saturation current of the p-n junction for different values of gate potential.

These two measuring techniques will be used before and after radiation.